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Method for electronic activation of a driver device of a piezoelectric actuator

The present invention relates to a method for electronic activation of the driver device of an ultrasonic piezoelectric actuator, and more particularly to a fuel injector having a piezoelectric stage activated by the electronic injection computer of an internal combustion engine in a motor vehicle.

More precisely, the problem that the invention is intended to solve is the activation of an electronic driver device that causes excitation of piezoelectric cells in order to make the structure of an injector vibrate, such a device being described in French Patent Application filed under No. 01-14023 in the name of the Applicant. A fuel injector containing an ultrasonic piezoelectric stage is intended to atomize the fuel very finely, with droplets whose size is gauged to ensure precise dosage and is sufficiently small that complete and homogeneous vaporization of the injected fuel is ensured. Such an injector is composed of, among other components, a cylindrical nozzle fed with fuel and provided at its end with an injection orifice, and of means, such as a transducer, for causing the nozzle to vibrate cyclically, comprising a piezoelectric ceramic stage, at the terminals of which the electric voltage is varied to modify its thickness between two extreme positions corresponding to opening and closing of the injector within a given reduction ratio. A piezoelectric ceramic stage of an injector is equivalent within a first approximation to a capacitor of high charging voltage, greater than about one hundred volts. This transducer is activated in duration and intensity by an electronic driver device, which itself is activated by the electronic control system of the engine to cause oscillating opening of the nozzle nose at ultrasonic frequency.

The electronic driver device is intended to generate a high-voltage AC signal, greater than about one hundred volts, at a high frequency, above about ten kilohertz, in order to excite the piezoelectric cells from a DC voltage source. In a motor vehicle, the battery delivers a supply voltage of 12 or 42 volts, which requires that this voltage must be boosted by a DC-to-DC step-up voltage converter supplied by the low voltage of the battery.

The purpose of the present invention is to activate electronically the driver switches of the driver device of the injectors, which switches are different from the injector-selection switches, and to do so relative to the load composed of a transformer, a resonance inductor and an injector.

The object of the invention is therefore a method for electronic activation of the driver device of at least one ultrasonic piezoelectric actuator from a control computer that is provided with a DC-to-AC step-up voltage converter supplied by a DC voltage source, the high-voltage output of which is connected to an oscillating circuit composed of the actuator and a resonance inductor, the said converter being composed of a circuit having at least one transformer with at least one primary winding connected to the voltage source by at least one drivable switch and a single secondary winding delivering an AC signal for excitation of the piezoelectric actuator, characterized in that:

- the voltage V_c at the terminals of the load composed of the transformer, resonance inductor and actuator is a square-wave signal of specified chopping frequency fr, and

- the current I_c flowing in the load is a periodic signal of resonance frequency f_o such that twice its value is greater than the chopping frequency f_r, $fr < 2 f_0$, in such a way that, upon closing of the switches, the current is zero in the circuit, this hypo-discontinuous type of mode of activation of the switches being obtained from the transformation ratio of the transformer and of the resonance inductor determined as a function of the equivalent capacitance of the actuator.

According to another characteristic, the method for electronic activation of the driver device of at least one ultrasonic piezoelectric actuator from a control computer that is provided with a DC-to-AC step-up voltage converter supplied by a DC voltage source, the high-voltage output of which is connected to an oscillating circuit composed of the actuator and a resonance inductor, the said converter being composed of a circuit having at least one transformer with at least one primary winding connected to the voltage source by at least one drivable switch and a single secondary winding delivering an AC signal for excitation of the piezoelectric actuator, is characterized in that:

- the voltage V_c at the terminals of the load composed of the transformer, resonance inductor and actuator is a square-wave signal of specified chopping frequency f_r,

- the current I_c flowing in the load is a periodic signal whose phase is advanced relative to the voltage V_c and whose resonance frequency f_o is such that the chopping frequency f_r lies between half and twice the resonance frequency, $f_o/2 < fr < 2 f_0$, in such a way that it activates zero-current closing of the switches in the driver switch, this hypo-continuous type of mode of activation of the switches being obtained from the transformation ratio of the transformer and of the resonance

inductor determined as a function of the equivalent capacitance of the actuator.

According to another characteristic, the method for electronic activation of the driver device of at least one ultrasonic piezoelectric actuator from a control computer that is provided with a DC-to-AC step-up voltage converter supplied by a DC voltage source, the high-voltage output of which is connected to an oscillating circuit composed of the actuator and a resonance inductor, the said converter being composed of a circuit having at least one transformer with at least one primary winding connected to the voltage source by at least one drivable switch and a single secondary winding delivering an AC signal for excitation of the piezoelectric actuator, is characterized in that:

- the voltage V_c at the terminals of the load composed of the transformer, resonance inductor and actuator is a square-wave signal of specified chopping frequency f_r,
- the current Ic flowing in the load is a periodic signal whose phase is retarded relative to the voltage V_c and whose resonance frequency f_o is such that the chopping frequency f_r is greater than half the resonance frequency, $f_r > f_0/2$, in such a way that it activates zero-voltage closing of the switches at the terminals of the driver switch, this hyper-continuous type of mode of activation of the switches being obtained from the transformation ratio of the transformer and of the resonance inductor determined as a function of the equivalent capacitance of the actuator.

Other characteristics and advantages of the invention will become apparent upon reading the description of several modes of electronic activation of a driver device of an ultrasonic piezoelectric actuator, illustrated by the following figures, which are:

- Fig. 1: the electronic schematic of an embodiment of a sequential driver device of a group of four ultrasonic piezoelectric actuators;
- Figs. 2a and 2b: the variations in time of the output voltage of the driver device and of the voltage at the terminals of a piezoelectric actuator;

- Fig. 3: the electronic schematic of an embodiment of a driver device in the bridge of a piezoelectric actuator;
- Fig. 4a: the waveform generated by the activation of the driver device in hypo-discontinuous mode according to the invention;
- Figs. 4b and 4d: the variations in time of the driving voltages at the terminals of the bridge transistors in hypo-discontinuous mode;
- Figs. 4c and 4e: representations of the voltages at the terminals of the bridge diodes in hypo-discontinuous mode;
- Fig. 5a: the waveform generated by the activation of the driver device in hypo-continuous mode according to the invention;
- Figs. 5b and 5d: the variations in time of the driving voltages at the terminals of the bridge transistors in hypo-continuous mode;
- Figs. 5c and 5e: representations of the voltages at the terminals of the bridge diodes in hypo-continuous mode;
- Fig. 6a: the waveform generated by the activation of the driver device in hyper-continuous mode according to the invention;
- Figs. 6b and 6d the variations in time of the driving voltages at the terminals of the bridge transistors in hyper-continuous mode;
- Figs. 6c and 6e: representations of the voltages at the terminals of the bridge diodes in hyper-continuous mode.

For these non-limitative examples of embodiments, elements bearing like references on the different figures perform like functions in order to achieve like results.

Since the invention comprises generating a sinusoidal signal of high voltage, greater than about one hundred volts, and of high frequency, greater than about ten kilohertz on the piezoelectric cell of each fuel injector of a vehicle from a DC voltage source, either the battery or the output of a power DC converter, it proposes the activation of a driver device according to different topologies that ensure excitation of the said piezoelectric ceramics via an inductor, in order to establish a resonant circuit. These topologies are described in the patent application cited hereinabove. These structures are valid for 1 to N injectors, where N is an integral number preferably equal to 4, 5, 6, 8, 10 or 12. As a non-limitative example, the number of driven injectors is 4 in the description hereinafter.

All the topologies described represent structures with at least one transformer having only a single winding in the secondary and one or two windings in the primary.

According to the schematic of Fig. 1, which represents a non-limitative structure with a single transformer, the driver device of one ultrasonic piezoelectric actuator I_i among four, where i is an integral number varying from 1 to 4, is provided with a source B of DC voltage E – such as a battery or the output of a DC-to-DC converter – whose (-) terminal is connected to ground and whose (+) terminal is connected to a bridge circuit whose center load is the primary winding L_1 of a transformer. This transformer comprises two windings wound around the same core, as shown by the asterisks in the schematic, a primary winding L_1 and a secondary winding L_2, whose high-voltage output V_s is connected to an oscillating circuit composed of the piezoelectric ceramic stage I_i and of a resonance inductor L. This resonance inductor is designed as a function of the operating frequency of the piezoelectric injector. It can also be placed in the primary of the transformer or even composed of the leakage inductor of the transformer.

This bridge circuit is established by two arms connected in parallel at the terminals of voltage source B and each composed of two alternately drivable series bridge switches P_1, P_2 and P_3, P_4 respectively, whose center points J_1 and J_2 respectively are connected to the two terminals of primary winding L_1.

In the case of an internal combustion engine of a motor vehicle that needs four injectors, the schematic represents four piezoelectric ceramics I_1, ... , I_i, ..., I_4, which are connected in parallel and, in a first embodiment, are successively chosen by virtue of a drivable selection switch K_i connected in series with each of them. The four injectors I_i are connected on the one hand to resonance inductor L, intended to form an oscillating circuit with each injector in succession, and on the other hand are connected in pairs by relays R_1 and R_2 respectively, each of which is connected to one terminal of a selection switch K_1 and K_2 respectively, whose other terminal is connected to ground. The injection computer first activates all relays then simultaneously the selection and bridge switches to select the injector to be driven, which must be open during the intervals of activity in order to ensure that fuel is fed to the corresponding cylinder of the engine.

The operation of this driver circuit is as follows, depending on how the different switches are driven. In a first phase, the driving signal sent by the injection computer activates on the one hand closing of the selection switch K_i connected to the chosen injector I_i and on the other hand simultaneous closing of bridge switches P_1 and P_4, thus connecting terminal J_1 of primary winding L_1 to the (+) terminal of battery B and terminal J_2 thereof to the (-) terminal of the battery. During this time interval between instants T_0 and T_1, the voltage v_1 at the terminals of primary winding L_1 is equal to +E, such that the voltage V_s at the terminals of the secondary winding L_2 is positive and equal to +mE by the effect of the transformation ratio, thus permitting loading through resonance inductor L of the actuator I_i selected by switch K_i activated by the computer. Then, in a second phase, during the following time interval between times T_1 and T_2, the signal drives switches P_1 and P_4 to open position and simultaneously drives the two switches P_2 and P_3 to closed position, thus connecting terminal J_1 of primary winding L_1 to the (-) terminal of battery B and terminal J_2 thereof to the (+) terminal, voltage v_i at its negative terminals being equal to -E. Thus the voltage V_s at the terminals of secondary winding L_2 becomes negative and equal to -mE. These two phases are repeated a large number of times during the injection period, which lasts for between 100 μs and 8 ms. The periodic voltage V_s at the terminals of secondary winding L_2 as a function of time is represented graphically in Fig. 2a. Voltage V_{ci} at the terminals of injector I_i is then a sinusoidal signal of the same period as voltage V_s at the terminals of secondary winding L_2, as shown in Fig. 2b, oscillating between a maximum value $+V_m$ and a minimum value $-V_m$. The injection computer then successively drives the other injectors I_i connected in parallel.

For excitation of injector I_1 between instants t_0 and t_1, the computer activates the relay R_1 into break position toward injector I_1 while relay R_2 is in break position, as well as the closing of switch K_1 and the opening of switch K_2, for the purpose of connecting actuator I_1 to resonance inductor L. Thus, between instants t_0 and t_1, the voltage V_s at the terminals of secondary winding L_2 is a periodic square-wave signal, oscillating between the extreme values +mE and -mE, and the voltage v_{c1} at the terminals of actuator I_1 is a sinusoidal signal oscillating between the extreme values +mGE and -mGE, where G is the resonance gain between resonance inductor L and the injector model, while the three other injectors do not receive any voltage. The closing duration T_{Ki} of each selection switch corresponds to the injection time, which can vary between 100 μs and 5 ms for a four-injector engine. The period T_{Pi} of the square-wave signal V_s at the terminals of the secondary winding of each transformer depends exclusively on the structure of the injectors, the resonance frequency F_{Pi}

varying between 10 kHz and 1 MHz.

Since the toggling of a relay from break position to make position is longer than the opening or closing of a switch, the computer activates toggling of second relay R_2 into make position at instant t_2 for the purpose of being able to excite injector I_3 at the following instant t_3.

At instant t_3, relay R_2 is toggled to make position while relay R_2 is still toggled to make position toward injector I_3, and simultaneously switch K_2 is closed until instant t_4 while switch K_1 has been open since instant t_1, such that voltage V_s at the terminals of secondary winding L_3 causes resonance of the oscillating circuit composed of inductor L and injector I_3 to which it is then connected. Voltage signal V_{c3} at the terminals of injector I_3 is a sinusoid of maximum amplitude mGE between the following instants t_3 and t_4.

Between the following instants t_5 and t_6, switch K_1 is reclosed and switch K_2 is opened, but relay R_1 is toggled toward injector I_2 and therefore its driving signal is inverted relative to that existing between instants t_0 and t_1. Thus voltage signal V_{c2} at the terminals of injector I_2 is a sinusoid of maximum amplitude mGE between the following instants t_5 and t_6.

Between the following instants t_7 and t_8, switch K_2 is reclosed while switch K_1 is opened, and the two relays R_1 and R_2 are in break position, therefore relay R_2 is toggled toward injector I_4, and its driving signal is inverted relative to that existing between instants t_3 and t_4. Thus voltage signal V_{c4} at the terminals of injector I_4 is a sinusoid of maximum amplitude mGE between the following instants t_7 and t_8.

The invention relates to precisely the activation of bridge driver switches with respect to the load C_h connecting the center points of the two bridge arms, this load being composed of the transformer, resonance inductor and actuator, or in other words being a function of the current I_c flowing in this load and of the voltage V_c at its terminals. In the practical example of Fig. 3, the bridge switches P_i are each composed of a transistor T_i and of a diode D_i connected in anti-parallel. For the periodic voltage V_s at the terminals of the secondary winding of the transformer to permit excitation of piezoelectric actuator I_i, the voltage V_c at the terminals of the load must be of square-wave form and of specified chopping frequency f_r.

According to a first characteristic of the invention, since the voltage V_c at the

terminals of the load composed of a transformer, resonance inductor and actuator is a square-wave signal of specified chopping frequency f_r, the current I_c flowing in the load is a periodic signal of resonance frequency f_o such that the chopping frequency f_r is at least two times smaller than it, $f_r < 2 f_o$, in such a way that, upon closing of the switches, the current is zero in the circuit. This type of hypo-discontinuous mode of activation of the driver switches is obtained from the values of the transformation ratio of the transformer and of the resonance inductor determined as a function of the value of the equivalent capacitance of the actuator. It makes it possible to limit the switching losses of the switches during their closing and to limit the effects of electromagnetic compatibility by current breaking.

The DC-to-AC step-up voltage converter is dimensioned such that the chopping frequency f_r needed to activate the piezoelectric injector is lower than twice the resonance frequency of the load.

Fig. 4a represents the waveform generated by the bridge of the driver device in hypo-discontinuous mode according to the invention.

To drive the given actuator I, the control computer activates on the one hand closing of selection means connected to the said actuator and on the other hand simultaneously, in a first phase, closing of a first pair of bridge switches composed of a first switch T_1 of the first arm and of a second switch T_4 of a second arm and the opening of the second pair formed by the two other switches T_2 and T_3 of the said arms and, in a second phase, the switching of the said four switches into an inverse position in such a way as to obtain a periodic voltage at the terminals of the secondary winding of the transformer, these two phases being repeated a specified number of times during the period of operation of the actuator to generate a high-voltage, high-frequency signal on the piezoelectric actuator from the DC voltage source.

Thus the sequencing of activation of the four switches of the driver device is as follows during two consecutive phases, the first of which takes place between instants t_0 and t_3 and the second takes place between instants t_3 and t_6.

At instant t_0 of starting of the first phase, transistors T_1 and T_4 are driven to closed position when current Ic is zero in diodes D_1 and D_4.

Between instants t_0 and t_1, these transistors T_1 and T_4 are closed to allow current I_c to flow, while diodes D_1 and D_4 are nonconducting, the voltage at their terminals being equal to +E.

At instant t_1, current I_c is inverted, the two diodes become conducting, the voltage at their terminals drops to zero and the two transistors T_1 and T_4 are driven to open position between this instant t_1 and instant t_2, at which the diodes are no longer conducting and the current drops to zero.

At instant t_3 of starting of the second phase, transistors T_2 and T_3 are driven to closed position when current I_c is zero in diodes D_2 and D_3.

Between instants t_3 and t_4, these transistors T_2 and T_3 are closed to allow current I_c to flow, while diodes D_2 and D_3 are nonconducting.

At instant t_4, current I_c is inverted, the two diodes become conducting and the two transistors T_2 and T_3 are driven to open position between this instant t_4 and instant t_5, at which the diodes are no longer conducting and the current again drops to zero.

Figs. 4b and 4d represent the variations in time of the driving voltages at the terminals of the bridge transistors, and Figs. 4c and 4e represent the voltages at the terminals of the diodes connected in parallel with these bridge transistors, or in other words their conducting or nonconducting states.

According to a second characteristic of the invention, since the voltage V_c at the terminals of the load composed of the transformer, resonance inductor and actuator is a square-wave signal of specified chopping frequency f_r, the current I_c flowing in the load is a periodic signal, whose phase is advanced relative to voltage V_c and whose resonance frequency f_o is such that the chopping frequency f_r is between half and twice the resonance frequency f_o, $f_o/2 < f_r < 2\ f_0$, in such a way that it activates zero current switching (ZCS) of the switches in the driver switch. This type of hypo-continuous mode of activation of the driver switches is obtained from the values of the transformation ratio of the transformer and of the resonance inductor determined as a function of the value of the equivalent capacitance of the actuator. Since this mode of activation of the driver switches is of the hypo-continuous type, it makes it possible to limit the switching losses of the switches

during their opening and to limit the effects of electromagnetic compatibility by current breaking.

The DC-to-AC step-up voltage converter is dimensioned such that the chopping frequency f_r needed to activate the piezoelectric injector satisfies the conditions indicated in the foregoing with respect to the resonance frequency f_o.

Fig. 5a represents the waveform generated by the bridge of the driver device in hypo-continuous mode according to the invention.

The sequencing of activation of the four switches T_1 to T_4 of the driver device is as follows during two consecutive phases, the first of which takes place between instants t0 and t2 and the second takes place between instants t_2 and t_4.

At instant t0, transistors T_1 and T_4 are driven to closed position when current I_c is zero in diodes D_1 and D_4 and when the other diodes D_2 and D_3 are conducting.

Between instants t_0 and t_1, these transistors T_1 and T_4 are closed to allow current I_c to flow, while the four diodes D_1 to D_4 are nonconducting.

At instant t_1, current I_c is inverted, the two diodes D_1 and D_4 become conducting and the two transistors T_1 and T_4 are driven to open position between this instant t1 and instant t_2, at which there is no current in these two transistors.

At this same instant t_2, transistors T_2 and T_3 are driven to closed position while diodes D_1 and D_4 are still conducting. At this instant of closing, diodes D_1 and D_4 are naturally nonconducting and current I_c flows in the same sense.

Between instants t_3 and t_4, current I_c is inverted and diodes D_2 and D_3 become conducting and these transistors T_2 and T_3 are driven to open position while there is no longer any current Ic present in these transistors.

At instant t_4, the two transistors T_1 and T_4 are driven to closed position, the two diodes D_2 and D_3 become nonconducting and activation recommences according to the same sequencing as between instants t_0 and t_4.

Figs. 5b and 5d represent the variations in time, in hypo-continuous mode, of the driving voltages at the terminals of the bridge transistors, and Figs. 5c and 5e represent the voltages at the terminals of the diodes connected in parallel with these bridge transistors, or in other words their conducting or nonconducting states.

According to a third characteristic of the invention, since the voltage V_c at the terminals of the load composed of the transformer, resonance inductor and actuator is a square-wave signal of specified chopping frequency fr, the current Ic flowing in the load is a periodic signal, whose phase is retarded relative to voltage V_c and whose resonance frequency f_o is such that the chopping frequency f_r is greater than half of the resonance frequency f_o, $f_r > f_0/2$, in such a way that it activates zero voltage switching at the terminals of the driver switch. This type of hyper-continuous mode of activation of the driver switches is obtained from the values of the transformation ratio of the transformer and of the resonance inductor determined as a function of the value of the equivalent capacitance of the actuator. This hyper-continuous mode of activation of the driver switches makes it possible to limit the switching losses of the switches during their opening and to limit the effects of electromagnetic compatibility by voltage switching. This mode of activation is of the zero voltage switching (ZVS) type for driving the switches to closed position.

The DC-to-AC step-up voltage converter is dimensioned such that the chopping frequency f_r needed to activate the piezoelectric injector satisfies the conditions indicated in the foregoing with respect to the resonance frequency f_o.

Fig. 6a represents the waveform generated by the bridge of the driver device in hyper-continuous mode according to the invention.

The sequencing of activation of the four switches of the driver device is as follows during two consecutive phases, the first of which takes place between instants t_0 and t_2 and the second takes place between instants t_2 and t_4.

Between instants t_0 and t_1, transistors T_1 and T_4 are driven to closed position while the two diodes D_1 and D_2 are conducting, and therefore while no voltage is present at the terminals of these transistors. The other diodes D_2 and D_3 are nonconducting and the two transistors T_2 and T_3 are open.

At instant t_1, diodes D_1 and D_4 are nonconducting.

Between instants t_1 and t_2, transistors T_1 and T_4 are still closed, allowing current I_c to flow.

At instant t_2, the transistors T_1 and T_4 are driven to open position, diodes D_2 and D_3 become conducting and voltage is no longer present at the terminals of transistors T_2 and T_3. Diodes D_1 and D_4 are nonconducting.

Between instants t_2 and t_3, transistors T_2 and T_3 are driven to closed position, after which they are driven to open position at instant t_4.

Figs. 6b and 6d represent the variations in time, in hyper-continuous mode, of the driving voltages at the terminals of the bridge transistors, and Figs. 6c and 6e represent the voltages at the terminals of the diodes connected in parallel with these bridge transistors, or in other words their conducting or nonconducting states.

According to another characteristic of the invention, the activation method combines, in time, the three modes of activation of the switches, or in other words the hypo-discontinuous, hypo-continuous and hyper-continuous types, as a function of the battery voltage E, which can vary, and of the peak setpoint voltage of the activation signal of the piezoelectric actuators.

The selection switches of the actuators and of the primary windings of the transformers are bidirectionally drivable in current, and for this purpose can be composed of two semiconductors connected in series or in parallel. As an example, they can be two transistors of the MOSFET type connected in series or of the IGBT type with antiparallel diode.

The actuator selection relays R are of monostable electromechanical type and have a break contact and a make contact.

As for bridge switches, if they are placed directly on the output side of the battery, they are preferably of the N-channel MOSFET type because of their low voltage drops. In the case in which they are placed on the output side of a DC-to-DC converter, these switches may be of the MOSFET or IGBT type.

As regards the transformer selection switches, they are preferably of the P-channel MOSFET type because of their low voltage drops.